Climate Change Analysis for Impact, Adaptation, & Policy: California's Water Resources

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http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/

Tantalus

In Hades, thirsty Tantalus was burdened to have water rise to his neck threatening to drown him, but receded when he stooped to drink. Above him was a boulder, threatening to crush him at some uncertain future time.

How like California water management!

Climate changes in California

- Historical Droughts
- Historical climate variability (ENSO, PDO, …)
- Paleo-droughts
- Sea level rise
- Climate warming
- Other form of climate change?

Climate Warming Effects?

- Shift in snowmelt season
- Changes in:
  - Watershed and reservoir ET
  - Crop ETAW and yields
  - Urban water use
  - Ecosystems (Temp., nutrients, CO_2, etc.)
- Wet or dry warming?

Some changes are clear, others uncertain.

Climate Warming and Water Supply Management

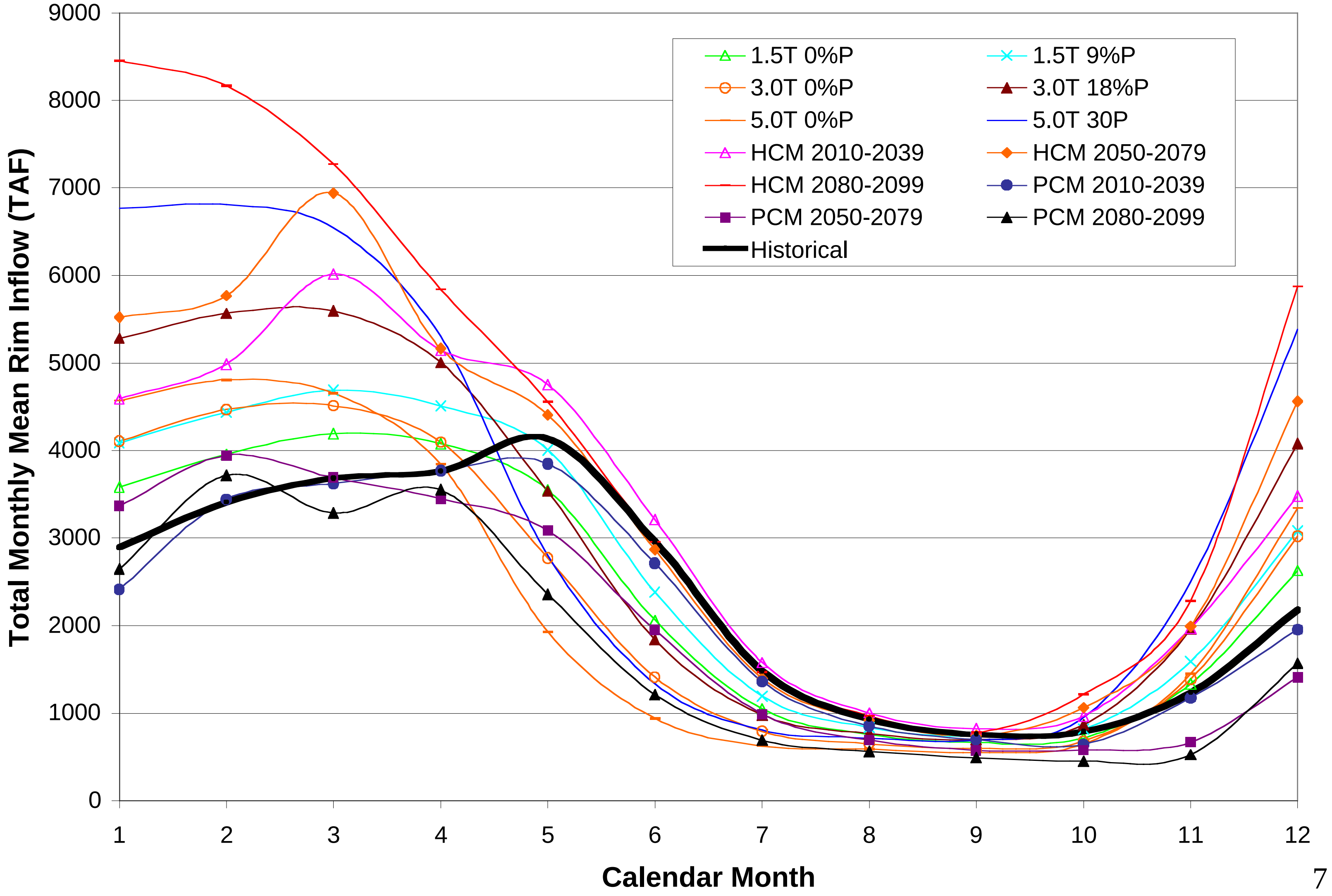
- Preliminary study of climate warming for water management in California
- 2100 climate warming and population growth scenarios
- CALVIN model identifies promising adaptations to climate and population changes
- Preliminary results

Thanks to California Energy Commission!

2100 Climate Warming

- Water availability changes estimated for 12 climate warming scenarios (based on LBNL).
- Water supply impacts estimated for:
  - Major mountain inflows
  - Groundwater inflows
  - Local streams
  - Reservoir evaporation
- Effects estimated for 113 inflows distributed throughout California

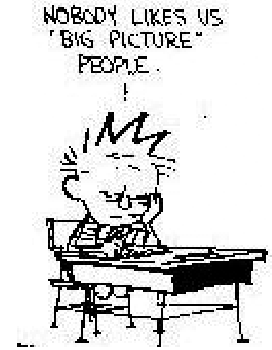
2100 Climate Warming



2100 Population & Land Use

- Future population and land use will greatly affect water demands.
- With growth to 92 million (UCB), urban demands grow by ~ 7.2 maf/yr
- Urbanization of irrigated land reduces agricultural demands by ~ 2.7 maf/yr
- Net effect is big (+4.5 maf/yr) and economically important

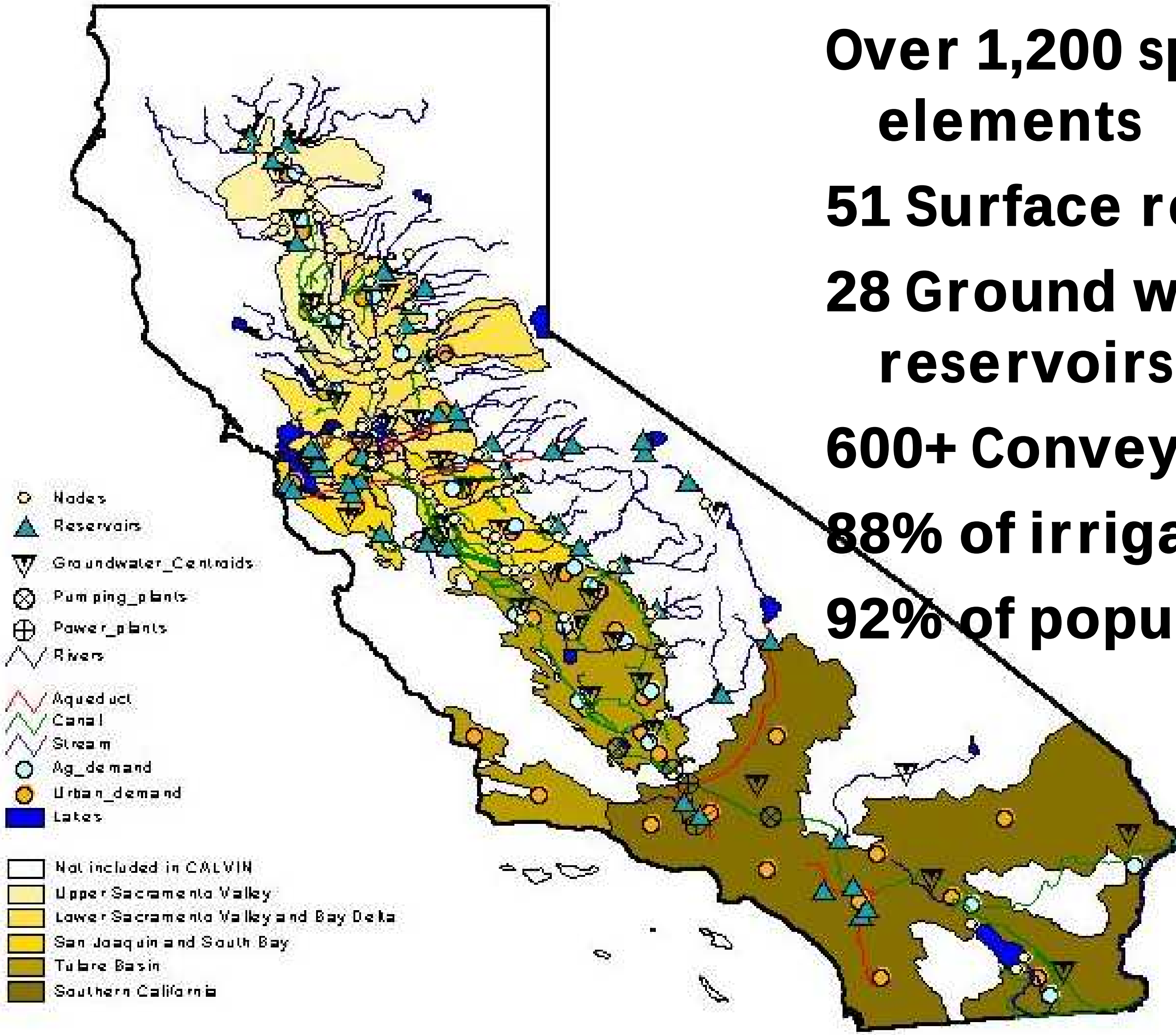
What is CALVIN?



- Model of entire inter-tied California water system
- Surface and groundwater systems; supply and demands
- Economics-driven optimization model
  - Economic Values for Agricultural, Urban, & Hydropower Uses
  - Flow Constraints for Environmental Uses
- Prescribes monthly system operation over a 72-year representative hydrology

Maximizes economic performance within constraints

CALVIN's Spatial Coverage



- **Over 1,200 spatial elements**
- **51 Surface reservoirs**
- **28 Ground water reservoirs**
- **600+ Conveyance Links**
- **88% of irrigated acreage**
- **92% of population**

Economic Values for Water

- Agricultural: Production model SWAP
- Urban: Demand model based on price elasticities
- Hydropower
- Operating Costs: Pumping, treatment, water quality, etc.

Environmental flows and deliveries as <u>constraints</u> – with first priority

Data Flow for the CALVIN Model

Inputs:

- Surface and ground water hydrology
- Physical facilities & capacities
- Environmental flow constraints
- Urban values of water (elasticities)
- Agricultural values of water (SWAP)
- Operating costs

CALVIN Economic Optimization Model:

Databases of Input & Meta - Data	HECPRM Solution Model

Outputs:

- Economic benefits of alternatives
- Conjunctive use & cooperative operations
- Willingness -to -pay for additional water & reliability
- Water operations & delivery reliabilities
- Value of more flexible operations
- Values of increased facility capacities

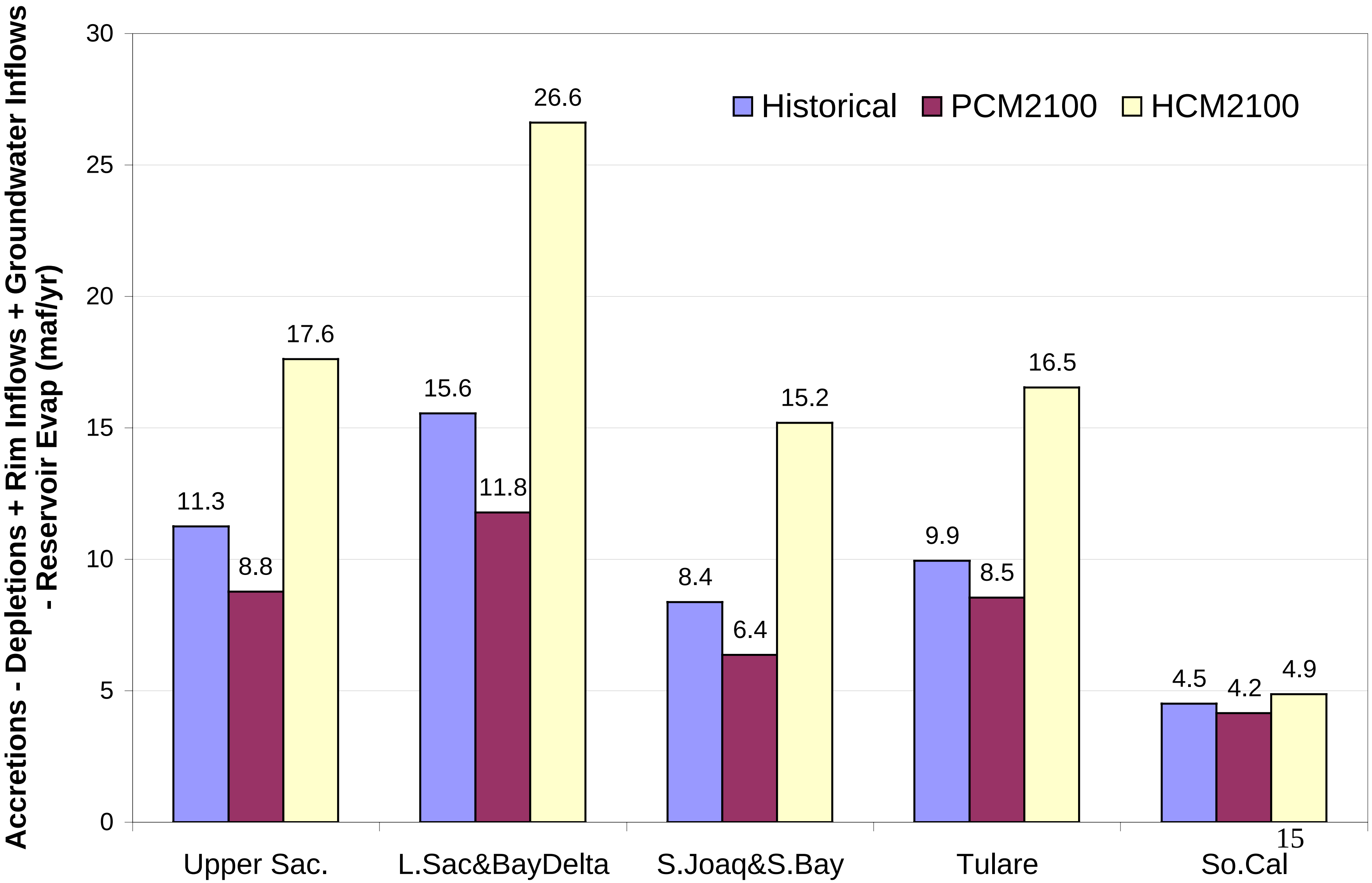
Integrated Adaptation Options

- Water allocation (markets & exchanges)
- System operations
    - Conjunctive use
    - Coordinated operations
- Urban conservation/use efficiencies
- Cropping changes and fallowing
- Agricultural water use efficiencies
- New technologies
    - Wastewater reuse
    - Seawater desalination

Alternative Conditions

- Base 2020 – Current policies for 2020
- SWM 2020 – Statewide water market 2020
- SWM 2100 – SWM2020 with 2100 demands
- PCM 2100 – SWM2100 with dry warming
- HCM 2100 – SWM2100 with wet warming

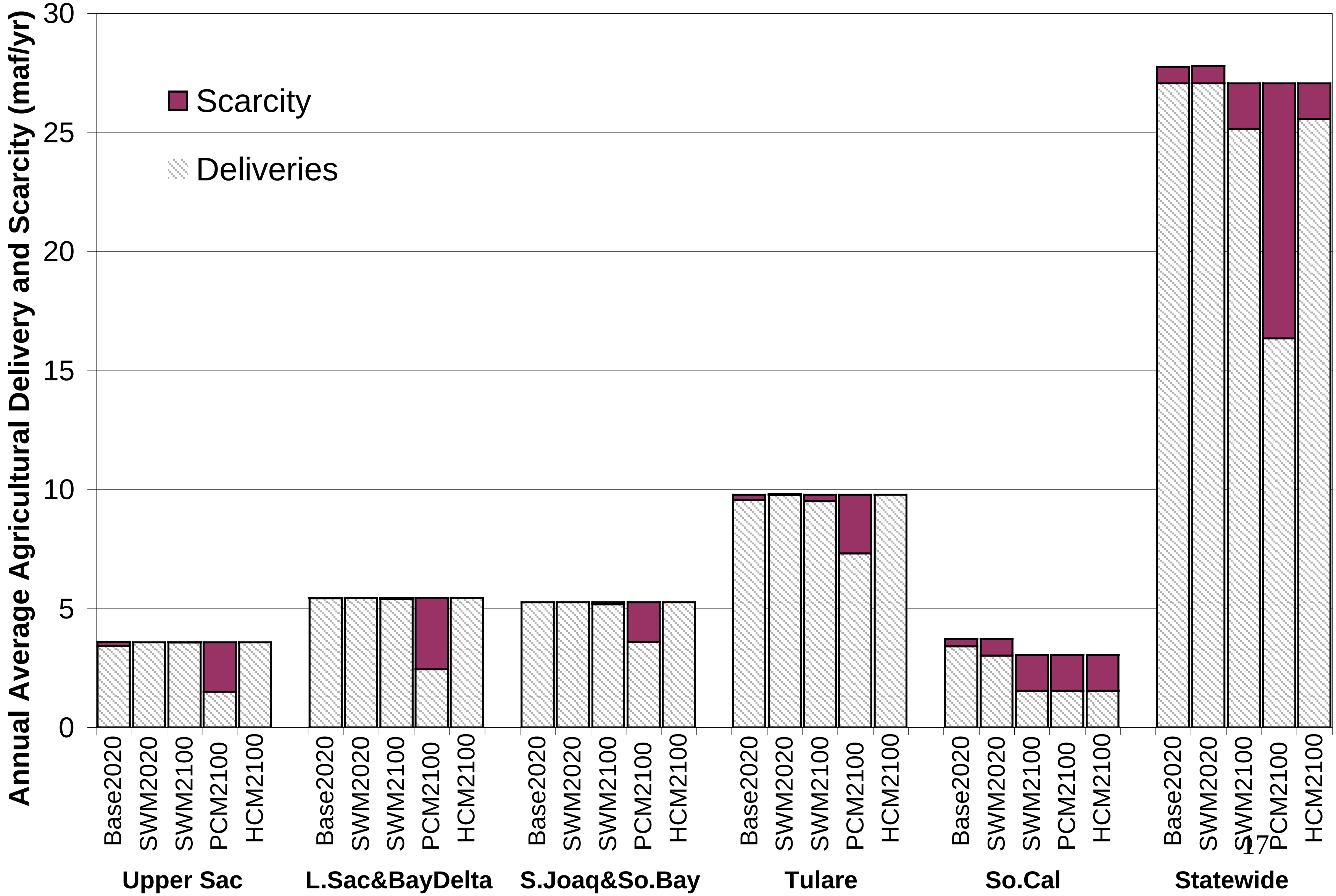
Climate Scenarios by Region



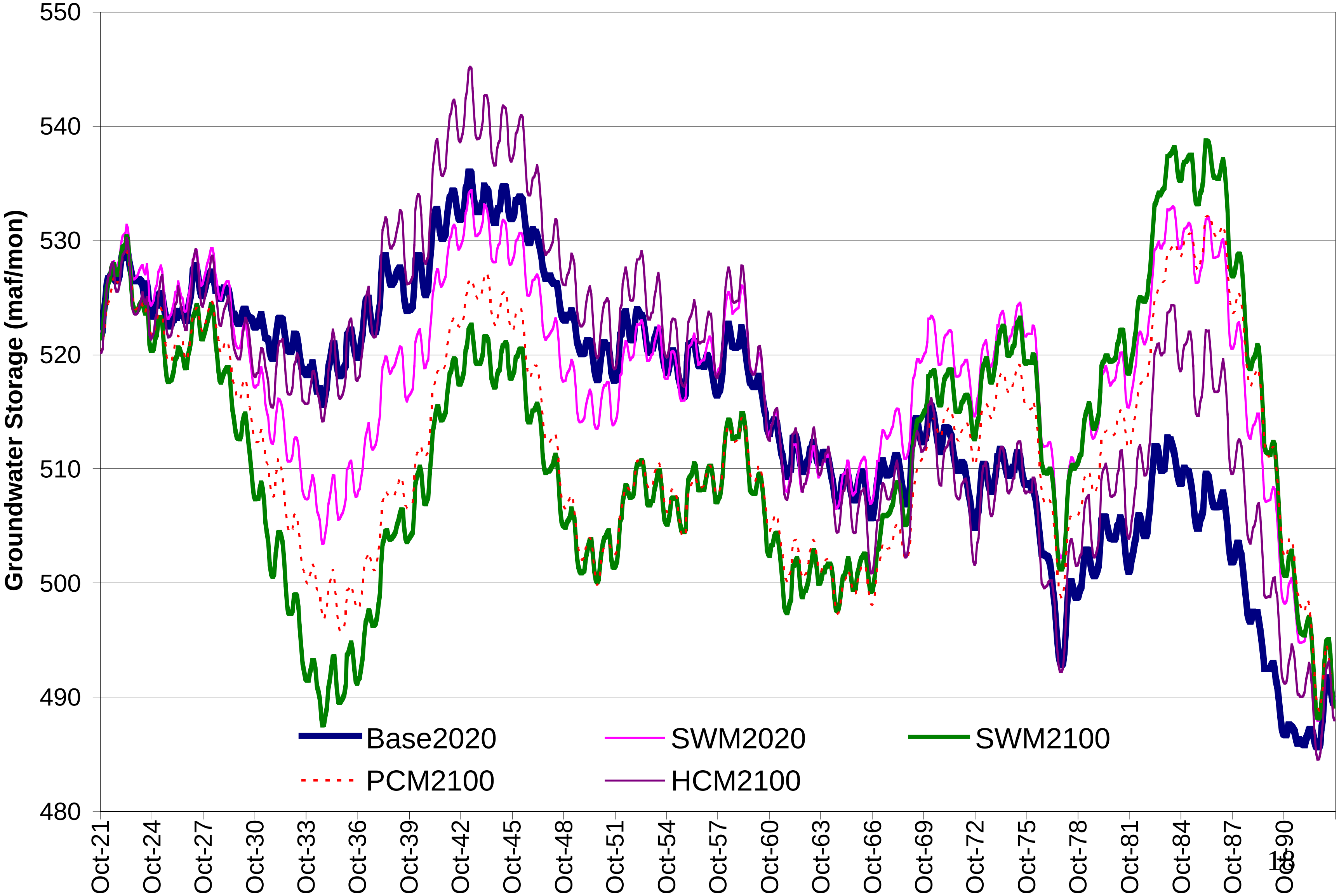
Scarcity, Operating, & Total Costs
($ million/yr)

Cost	**Base 2020**	**SWM 2020**	**SWM 2100**	**PCM 2100**	**HCM 2100**
Urban Scarcity	1,564	170	785	872	782
Agric. Scarcity	32	29	198	1,774	180
Operating	2,581	2,580	5,918	6,065	5,681
Total Costs	**4,176**	**2,780**	**6,902**	**8,711**	**6,643**

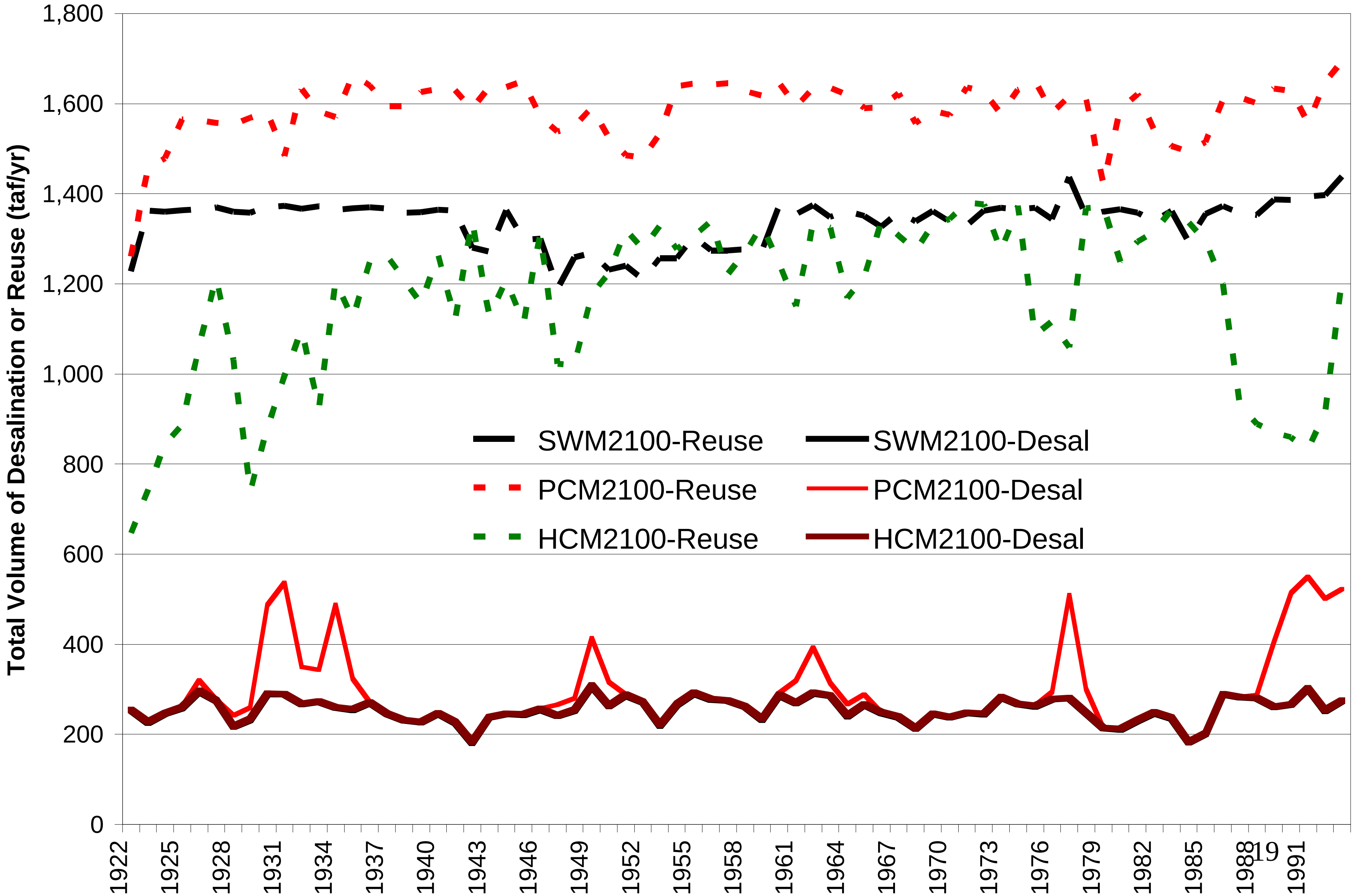
Agricultural Deliveries & Scarcities



Groundwater Operations



New Source Technologies



Environmental Flow Costs

Minimum Instream Flows	Average WTP ($/af) SWM2020	SWM2100	PCM2100	HCM2100
Trinity River	0.6	45.4	1010.9	28.9
Sac. R. at Keswick	0.1	3.9	665.2	3.2
Mokelumne River	0.1	20.7	332.0	0.0
Yuba River	0.0	0.0	1.6	1.0
Merced River	0.7	16.9	70.0	1.2
Mono Lake Inflows	819.0	1254.5	1301.0	63.9
Owens Lk. Dust Mitigation	610.4	1019.1	1046.1	2.5
Refuges				
Sac West Refuge	0.3	11.1	231.0	0.1
SJ/Mendota Refuges	14.7	32.6	249.7	10.6
Pixley Refuge	24.8	50.6	339.5	12.3
Kern refuge	33.4	57.0	376.9	35.9
Delta Outflow	**0.1**	**9.7**	**228.9**	**0.0**

Economic Value of Facility Changes

($/unit-yr)

Surface Reservoir (taf)	**SWM2100**	**PCM**	**HCM**
Turlock Reservoir	69	202	56
Santa Clara Aggregate	69	202	56
Pardee Reservoir	68	202	56
Pine Flat Reservoir	66	198	56
New Bullards Bar Reservoir	65	196	56
Conveyance (taf/mo)			
Lower Cherry Creek Aqueduct	7886	8144	7025
All American Canal	7379	7613	6528
Putah S. Canal	7378	7611	6528
Mokelumne Aqueduct	7180	7609	6301
Coachella Canal	3804	3487	3618
Colorado Aqueduct	1063	970	759
California Aqueduct	669	1823	452

Conclusions from Results

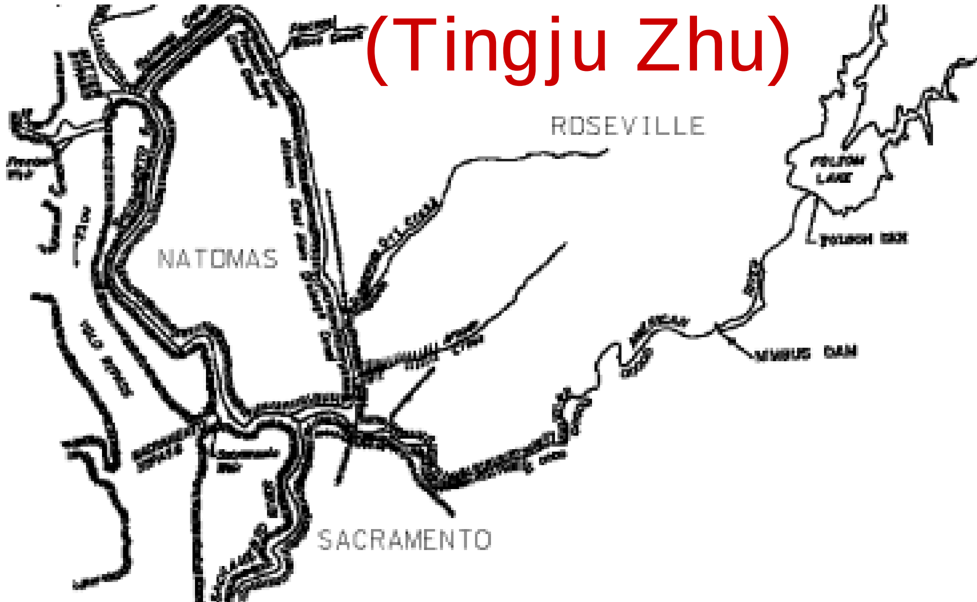
- Climate warming's hydrologic effects are substantiated and generalized.
- Future water demands matter too! Similar magnitude to climate warming effects.
- Must also allow future adaptations – Optimization should include many options.
- California's system can adapt, at some cost.

Conclusions from Results (con't)

- Central Valley agriculture sensitive to dry warming
- Urban S. Calif. less sensitive to warming
- Flooding problems
- Adaptation would be challenging
  Institutional flexibility needed to respond to both population and climate changes.
- Study has limitations. But it is worthwhile considering management and policy changes.

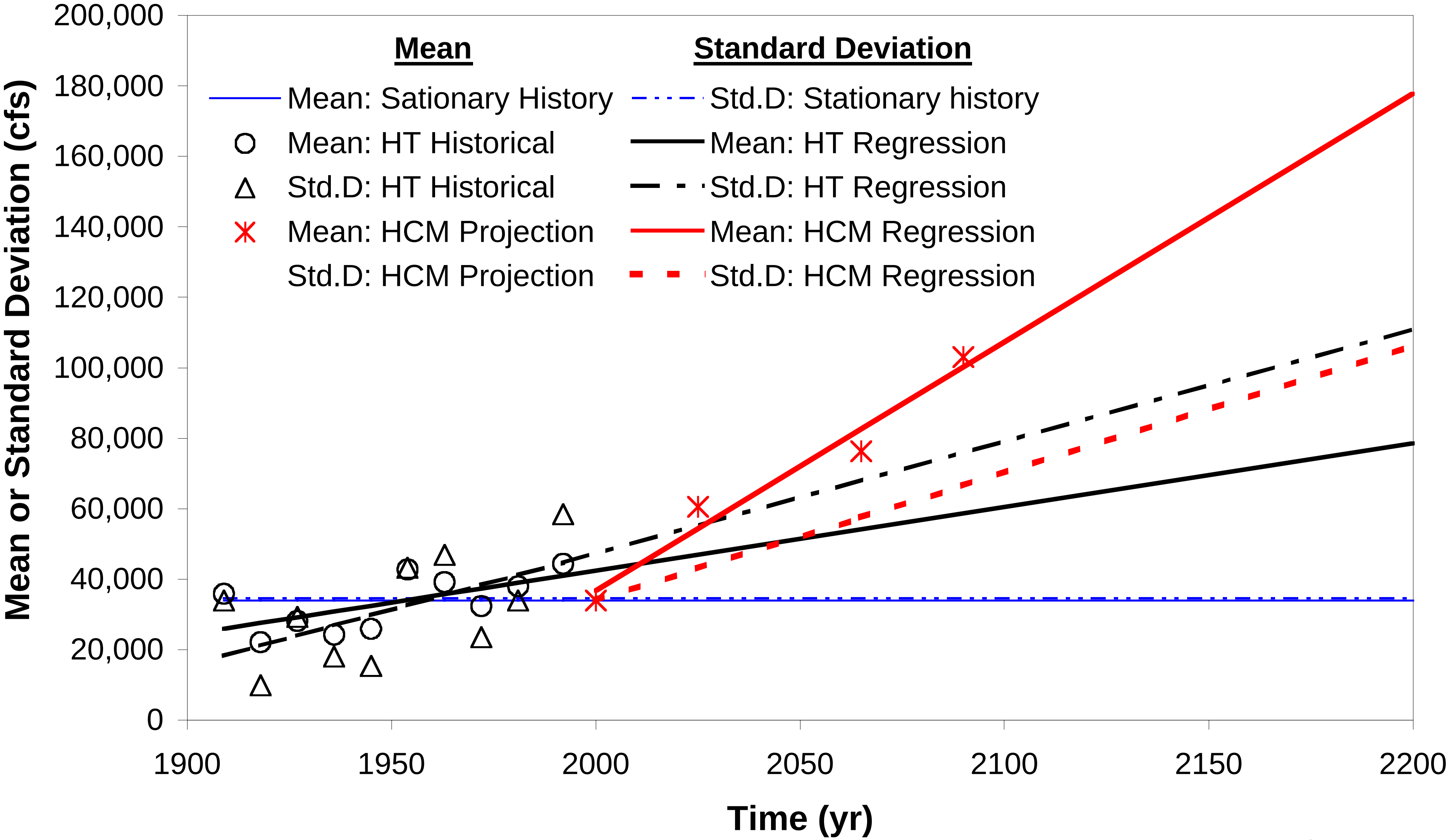
Flooding on the Lower American River

(Tingju Zhu)



What are long-term optimal levee heights and levee setbacks, given different climate change scenarios and increasing urban values for floodplain land?

Three-Day Peak Inflows at Folsom Lake



Optimization Formulation

Maximize net PV of urban and riparian land value benefits minus costs of flood damage, levee height and setback over 200+ years. Decisions are levee height and setback.

<u>Solution by Stochastic Dynamic Programming</u>

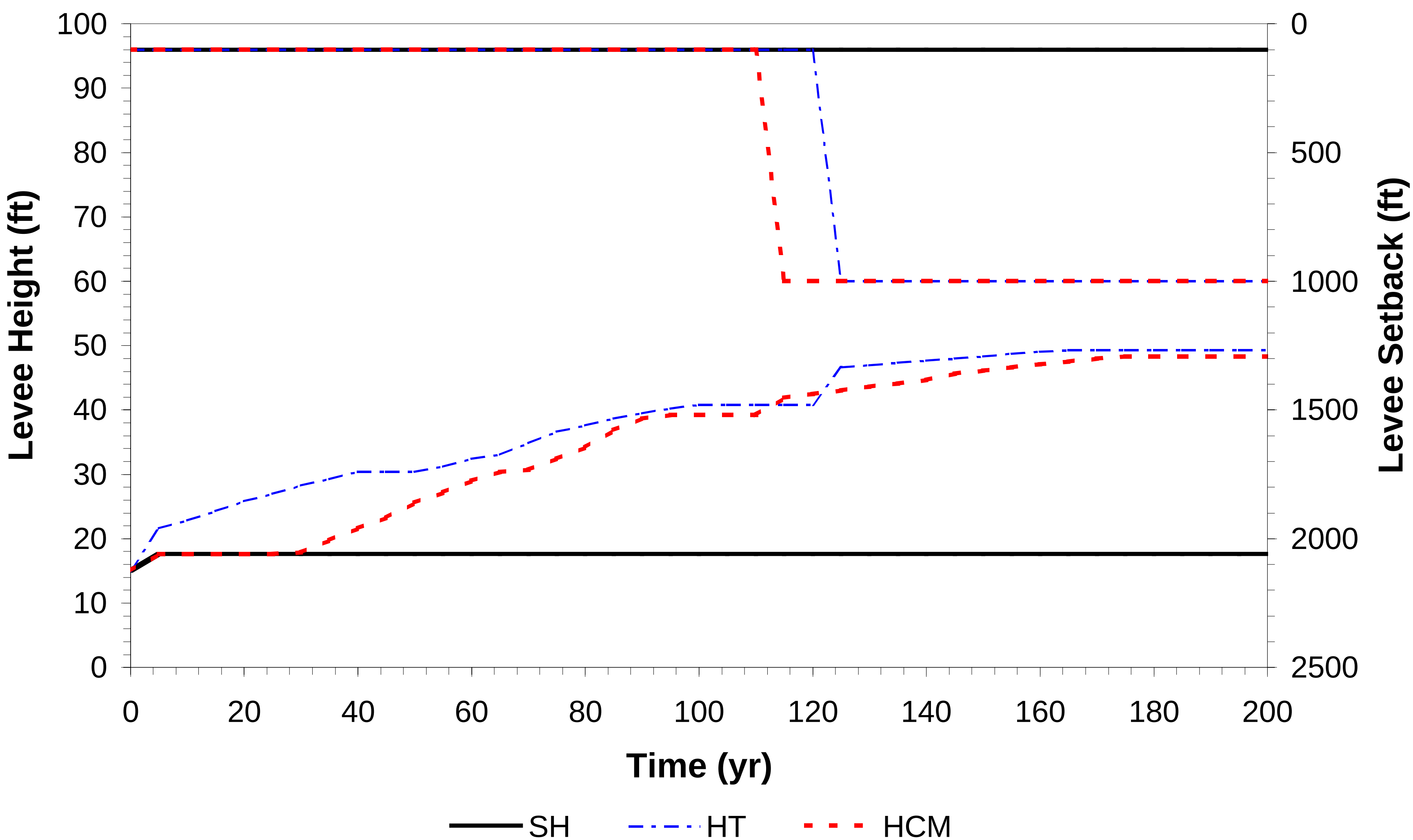
- Recursive Equation $f_t\left(\overrightarrow{S_t}, \overrightarrow{X_t}\right) = \begin{cases} \max\limits_{X_t}\left\{\left[\sum\limits_j P_t\left(j \mid \overrightarrow{X_t}\right) B_{jt}\left(\overrightarrow{S_t}, \overrightarrow{X_t}\right)\right] + f_{t+1}\left(\overrightarrow{S_{t+1}}, \overrightarrow{X_{t+1}}\right) e^{-r\cdot\Delta t}\right\}, & t < N \\ V\left(\overrightarrow{X_N}\right) & t = N \end{cases}$

NorthBankLeveeHeightNorthBankSetbackSou

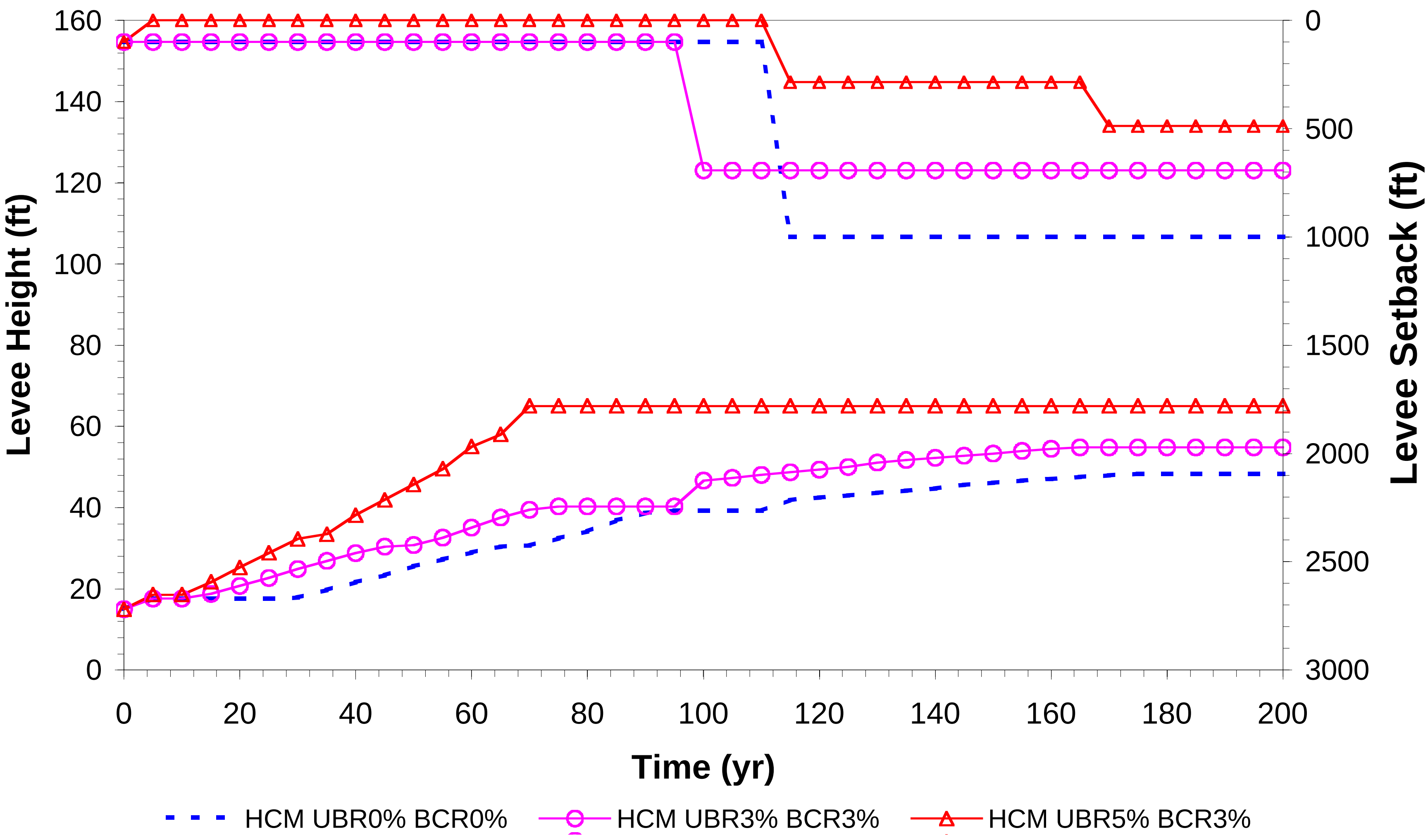
- Salvage Value of Levees $V\left(\overrightarrow{S_N}\right) = \left[\sum\limits_j P_N\left(j \mid \overrightarrow{S_N}\right) B_{jN}\left(\overrightarrow{S_N}\right)\right] \dfrac{e^r}{e^r - 1}$

- State Transition Equation $\overrightarrow{S_{t+1}} = \overrightarrow{X_t}$
- Levee Height Limit
- DDDP accelerates and improves problem solution

Climate Change Effects



Urbanization Effects under HadCM2 Scenario



Flood Control Conclusions

- Climate change and urbanization affects flood damage and optimal long-term flood management.
- Framework for long term flood control analysis with climate change and urbanization
- Economically optimal interaction of multiple flood control decisions over the long term with changing economic and climatic conditions
- Would be good to add more adaptation options
- Likely economic value to expanding lower American River setbacks and levee heights in the future. Zoning implications of widening setbacks in ~100 years.

Overall Conclusions

Adaptation and impact studies of climate change almost require:

- Broader view of hydrology (esp. GW)
- Broader view of water management options
- Including other major long-term changes
- Optimization modeling
- Cautious interpretation

Most studies are still rather primitive.

http://cee.engr.ucdavis.edu/faculty/lund/CALVIN/

Lund's climate change conjecture

Policy advocates will use climate change as a reason for whatever they would advocate without climate change.

Examples: new storage, environmental restoration, water conservation, population control

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